Design Science

Design of urban electric bus systems

Dietmar Göhlich[1], Tu-Anh Fay[1], Dominic Jefferies[1], Enrico Lauth[1], Alexander Kunith[1] and Xudong Zhang[2]

1 *Department of Methods for Product Development and Mechatronics, Research Team Electric Transport Solutions, Technische Universität Berlin, 10623 Berlin, Germany*
2 *National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology, 100081 Beijing, China*

Abstract

Many public transport authorities have a great interest in introducing zero-emission electric buses. However, the transformation process from diesel to electric bus systems opens up a vast design space which seems prohibitive for a systematic decision making process. We present a holistic design methodology to identify the 'most suitable system solution' under given strategic and operational requirements. The relevant vehicle technologies and charging systems are analysed and structured using a morphological matrix. A modular simulation model is introduced which takes technical and operational aspects into account. The model can be used to determine a feasible electric bus system. The technology selection is based on a detailed economic analysis which is conducted by means of a total cost of ownership (TCO) model. To cope with uncertainties in forecasting, a stochastic modelling of critical input parameters is applied and three different future scenarios are evaluated. The applicability of the model was verified in a pilot project in Berlin and the methodology was applied to a realistic operational scenario. Our results indicate that electric bus systems are technically feasible and can become economically competitive from the year 2025 under the conditions examined.

Key words: urban electric bus systems, battery and charging technologies, bus system simulation model, economic analysis, total cost of ownership, technology selection

the **Design Society**
a worldwide community

CAMBRIDGE
UNIVERSITY PRESS

1. Introduction, related work and methodology

In the European Union, transportation is responsible for about one quarter of all greenhouse gas emissions because over 90% of the fuel used for transportation is petroleum based (European Union 2017). Additionally, cars, trucks and buses are responsible for other noxious or toxic substances, such as carbon monoxide from incomplete combustion, hydrocarbons from unburnt fuel, nitrogen oxides from excessive combustion temperatures, and particulate matter. To achieve ambitious climate goals, e.g., the reduction of CO_2 emissions by 60% in 2040 in the European Union (European Commission 2011) and to improve air quality especially in urban areas, 'clean technologies' have to be developed and deployed in all sectors of transportation.

Therefore, public transport authorities have a great interest in introducing zero-emission buses (Faltenbacher *et al.* 2016). However, replacing today's fleets of diesel buses entails several challenges. First, electric buses – apart from catenary based trolley bus systems – only recently have become commercially available and

they still need further technical improvements. Second, bus operators face several different options of electric bus and charging technologies and a vast number of possibilities to combine these options into a system solution. All options have specific assets and drawbacks concerning technological complexity, capital and operational cost.

Different aspects of this far-reaching transformation have been covered in numerous papers. Sinhuber, Rohlfs & Sauer (2012) and Rogge, Wollny & Sauer (2015) used a simulation model to determine the route specific energy consumption and calculate the required battery size. Rogge *et al.* (2015) further discussed the trade-off between passenger and battery capacity and the interdependency between charging power and battery capacity in order to electrify an existing bus network. The energy consumption in both studies is calculated under cooling condition. Jefferies *et al.* (2015) investigated the energy consumption for heating and cooling in detail and showed that heating is the most critical condition if zero-emission operation (i.e., purely electric heating) is required.

Battery sizing is investigated in Gao *et al.* (2017). The researchers concluded that the operational requirements and the charging concept affect the battery size and design significantly. The study of Mahmoud *et al.* (2016) presents a review of alternative powertrains based on results of simulation models and operational data from the literature. The study is a comparative analysis of 16 performance features for electric powertrains including economic, environmental, operational, and energy efficiency aspects. The study reveals the complexity of such systems and the challenge to compare different operating methods objectively.

Generic economic assessments of electric buses can be found in Göhlich, Spangenberg & Kunith (2013), Nurhadi, Borén & Ny (2014) and Pihlatie *et al.* (2014). The researchers analyse possible cost drivers of a line electrification and put a focus on the impact of operational constraints.

So far, only very limited research has been published which combines technology, operational and economical aspects in an integrated system approach. Rothgang *et al.* (2015) analyse the design process for electric public buses based on a standard 12 m and a 7 m battery-electric bus with focus on the battery design. The researchers also used a simple life-cycle cost model and evaluated the impact of a defined fuel cost increase and defined battery cost decrease on the overall costs per kilometre. Lajunen & Lipman (2016) evaluate the life-cycle costs and the well-to-wheel carbon dioxide emissions of different types of city buses and different routes. However, in these studies neither additional energy for heating and air conditioning nor additional staff cost caused by electrification has been included. Uncertainties in cost development of electric bus systems were not discussed. Moreover, the strategic question of the appropriate procurement time also remains to be addressed.

This study presents a holistic design methodology for urban electric bus systems based on technical feasibility assessment and TCO (total cost of ownership) as a key performance indicator. Figure 1 visualises the proposed methodology. The design of an urban electric bus system is based on operational data and assumptions discussed in Sections 3 and 4. Our approach combines technical, operational and economical aspects based on two core models: A system simulation model explained in Section 5 and a TCO model described in Section 6.
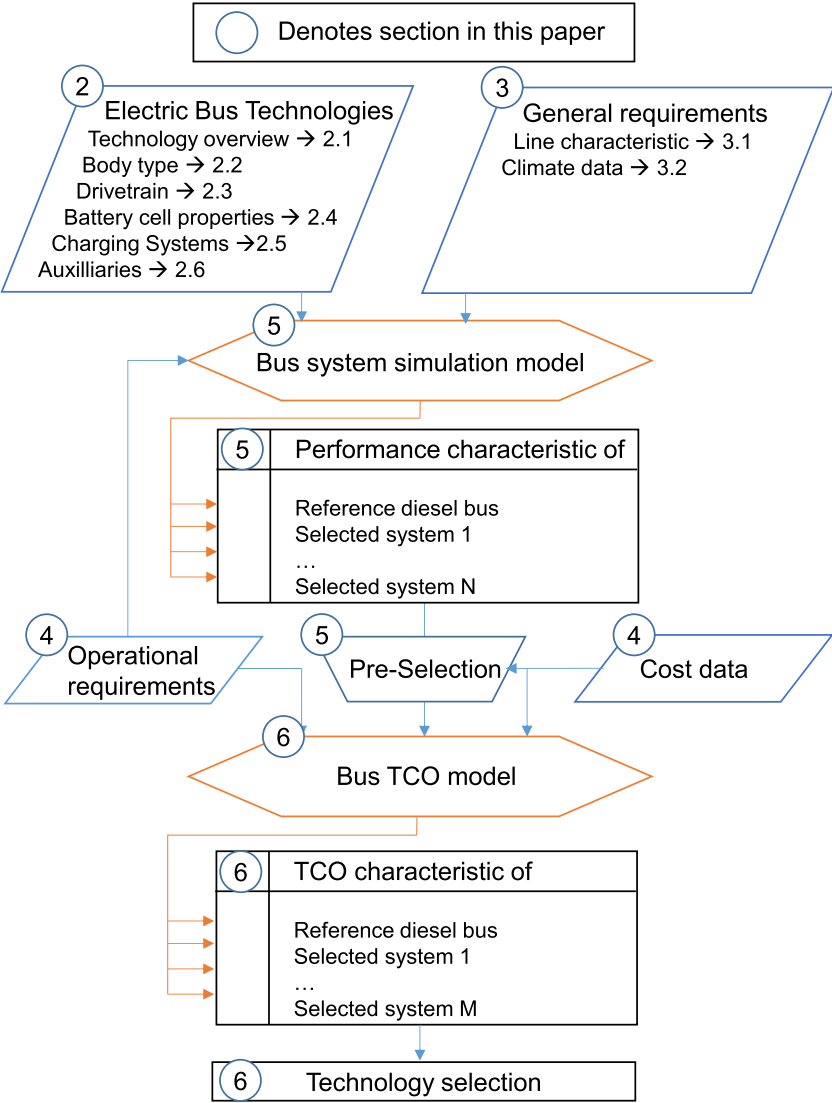
Figure 1. Holistic design methodology for electric bus technologies.

2. Urban electric bus technologies

In this section, we will give an overview of relevant components in electric bus systems and discuss the technical parameters most important for electric bus system design.

2.1. Functions and technology options

The morphological matrix method was applied to illustrate the complexity of designing an electric bus system. We derived a matrix of nine different functions with up to six options each, as shown in Figure 2. This leads to over 100,000 different system solutions which are theoretically possible.

Function	Options					
	grid				**local storage**	
energy source	low voltage	medium voltage	high voltage	rail	stationary battery	H$_2$ tank
charging/ refueling strategy	opportunity	in motion	depot			
charging/ refueling interface	manual (plug, pump nozzle)	pantograph	induction	trolleybus current collector	battery swapping	
on-board energy source	**battery**			capacitor	H$_2$ tank (+ fuel cell)	none
	NMC	LFP	LTO			
drive motor	permanent magnet synchronous	electrically excited synchronous	asynchronous	switched reluctance		
drive topology	central motor	wheel hub motor				
body type	12 m single-deck	18 m articulated	24 m bi-articulated	double-deck		
cooling	electric air-conditioning	none				
heating	electric resistance heating	electric heat pump	fuel heating			

Figure 2. Morphological matrix of available technology options in electric bus systems.

For this study, we limit the system boundary to include the vehicles on the route and the necessary charging infrastructure at terminal stops and in the depot. Changes to the processes in the bus depot are not within the scope of this study.

The electric bus system has been divided into six main functions (coloured): energy source, charging/refuelling strategy and interface, on-board storage, drive motor and topology, bus type as well as cooling and heating. Here, the interaction of the charging/refuelling strategy and interface with the on-board storage will play a decisive role in the overall design. Three different strategies were identified:

- Opportunity charging (OC), also referred to as fast charging: the batteries are charged several times during operation, usually during dwell times at terminal stations, by automated charging systems (pantograph or induction system). The daily range is therefore theoretically unlimited and is only limited by cleaning and maintenance procedures in the depot. Since only short dwell times are available, high charging power is required.

- In motion charging: the roadway of the buses is partially equipped with an overhead cable, which is connected with the vehicle by means of a current collector. The batteries are charged while driving under the overhead cable, so that the energy for route segments without overhead wires can be supplied by the battery storage. The daily range is also theoretically unlimited.

Table 1. Overview of common urban bus body types. Typical empty weight refers to conventional diesel buses. Sources: MAN Nutzfahrzeuge Gruppe (2008), Berliner Verkehrsbetriebe AöR (2013, 2016), European Union (2015) and Omnibus Revue (2017)

Body type	Length [m]	EU GVW [t]	Typical empty weight [t]	Max. payload [t]	Max. no. passengers
12 m single-deck	12	19.5	11.6	7.9	115
18 m articulated	18–18.75	28[1]	17.3	10.7	156
25 m bi-articulated	24.8	36	22.3	13.7	200
2-axle double-deck	10.5–12	19.5	12.5	7.0	101
3-axle double-deck	12–13.7	26	17.3	8.7	126

- Depot charging (DC): the battery is only charged during the operating pause in the depot, usually with a manual plug. The maximum range of such buses is currently about 200–300 km. Depot charging is also known as overnight or slow charging.

In the case of battery-electric buses, battery charging can be physically decoupled from the vehicle by means of battery swapping stations. These feature stationary battery charging banks and an automated system to transfer battery packs between charging bank and vehicle.

The on-board storage can be realised through four different options, in which a combination of several options is also possible: battery, super capacitor, hydrogen fuel tank or none, which is only possible with a continuous energy supply via overhead wires.

The proposed method is applicable to all technologies but within the scope of this article, we assumed that a (local) zero-emission operation is sought. Therefore, only the pure electric drive is taken into account and hybrid options have been excluded. Furthermore, battery swapping and trolley bus systems are not included in this study because battery-electric bus projects in recent years have been focused nearly exclusively on depot and opportunity charging (ZeEUS Project 2016). Also, fuel cell bus systems are excluded because the expenditures for fuel cell buses, including the necessary hydrogen infrastructure, have been shown to be significantly higher than for battery-electric buses. The studies FCH JU (2012) and Roland (2015) predict an approximate cost parity for fuel cell and conventional diesel buses not before the year 2030; whereas, battery-electric buses are promising to achieve cost savings considerably earlier in time.

But even with this reduced number of options we still face the need for a methodical identification of a 'most suitable system solution' under given strategic and operational requirements.

2.2. Vehicle body and passenger capacity

Electric buses are based on the same vehicle bodies as diesel buses. Table 1 lists typical body types used in metropolitan bus services.

[1] 29 t for alternatively fuelled vehicles.
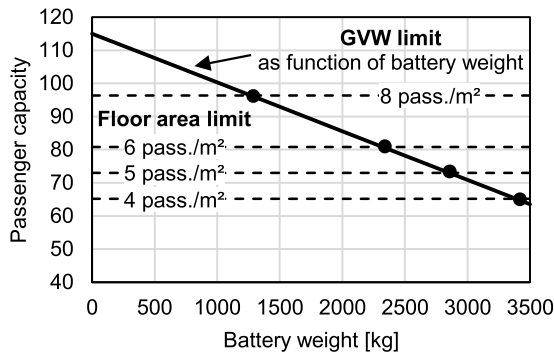
Figure 3. Passenger capacity of a 12 m bus by GVW as a function of added battery weight, and passenger capacity.

Our market surveys have shown that currently, the market for battery buses is dominated by standard 12 m buses and 18 m articulated buses. Fully electric double-decker buses are still at the prototype stage. 25 m bi-articulated buses are currently only encountered in the form of trolley buses.

Table 1 also specifies the respective gross vehicle weight (GVW) permitted by EU regulations, typical empty masses and the resulting payload and passenger capacity.[2] Although the empty weight is taken from datasheets for diesel buses, it can still serve as a valid basis for electric bus system design because the empty mass of diesel buses and electric buses excluding traction batteries and charging equipment can be assumed to be roughly equal. We have verified this for a 12 m vehicle based on confidential manufacturers' data.

The weight of an electric bus battery can be on the order of several tons, giving rise to an apparent conflict between battery capacity and passenger capacity. However, it is reasonable to assume that the practical maximum passenger capacity is not limited by payload, but rather by the floor space available to standees. The standee density achieved at full payload represents extreme crush-loading levels that, arguably, do not reflect realistic operating conditions.[3] Designing the vehicle for a passenger capacity determined by floor space leaves ample weight reserve for traction batteries even under crowded conditions, as Figure 3 illustrates for a 12 m bus. In this example, even assuming a passenger density of $8/m^2$, a battery weighing close to 1.3 tons could be added without exceeding the GVW of 19.5 tons.

2.3. Powertrain

A typical electric bus powertrain configuration consists of an energy source (e.g., battery), a single traction motor with controller and a final drive differential

---

[2] Maximum passenger capacity of urban buses is commonly calculated assuming an average weight of 68 kg per person (MAN Nutzfahrzeuge Gruppe 2008).

[3] Example: In the case of a standard 12 m bus with an available floor area of 7.8 m^2 and additional space for 34 seated passengers (MAN Nutzfahrzeuge Gruppe 2008), the maximum number of passengers calculated by payload in Table 1 would lead to a density of 10.4 standees per m^2. By comparison, passenger densities in excess of $5/m^2$ are considered 'crush loading' by the U.S. Transportation Research Board. The International Association of Public Transport (UITP) uses four standees/m^2 as a benchmark for unacceptable crowding (Li & Hensher 2013).
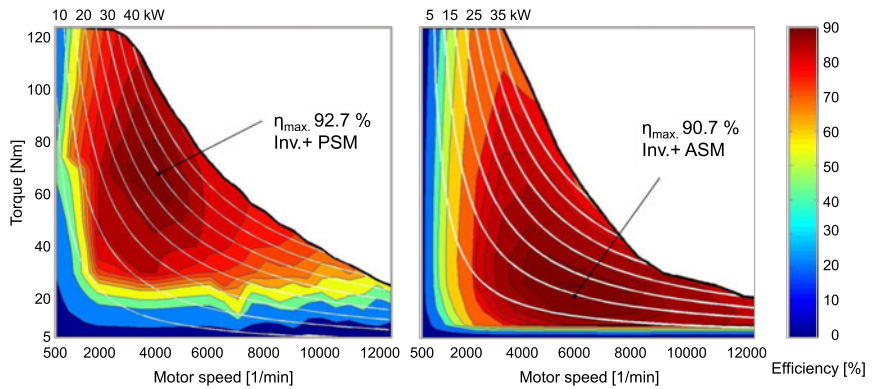
Figure 4. Typical efficiency maps of synchronous (PSM) and asynchronous motor (ASM) (Neudorfer 2016).

gearbox. Alternative configurations are two traction motors with reduction gears near the wheels or two to four in wheel motors (Lajunen 2014). These configurations with multiple traction motors can use a simple torque splitting or a specific driving and regenerative braking regulation design can be used to optimise the vehicle efficiency, as shown in Zhang & Goehlich (2016).

According to the ZeEUS Project (2016) the majority of bus suppliers (20/26) have single traction central motors using asynchronous motor (ASM) or permanent magnet synchronous motor (PSM). The power peak ranges from 100 kW to 480 kW for 8 m–24 m buses.

For the system design, the crucial information is the characteristic of the powertrain. Figure 4 shows typical efficiency maps of a PSM and an ASM including the efficiency of the inverter (Inv.). In general, synchronous motors have high efficiency at low motor speed and high torque, whereas the asynchronous machine is more efficient at high speed and low torque.

Currently, both types can be found in bus systems, because in actual system design, packaging, motor control and cost are further parameters that need to be examined. Permanent magnet synchronous motors have advantages in mass and have higher efficiencies in the nominal operating point, but are more costly due to permanent magnets and manufacturing issues (Neudorfer 2016).

2.4. Battery system

While nearly all modern electric vehicles feature some form of lithium-based battery (Thielmann *et al.* 2017), various cell chemistries exist whose technical parameters differ significantly. The most important characteristics of a specific cell type with regard to electric bus operations are energy density, charge rate and cycle life.

Currently, lithium iron phosphate (LFP), lithium titanium oxide (LTO) and lithium nickel manganese cobalt oxide (NMC) are the most common cell types encountered in electric buses, as our surveys of electric bus projects indicate. Table 2 shows typical parameters for these cell types from catalogue data. For the sake of comparability, only pouch-type cells are considered. Figure 5 indicates
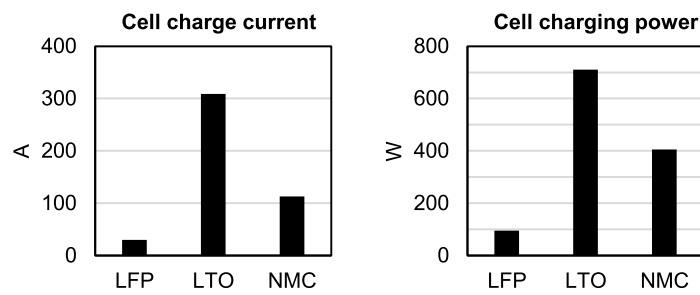
Figure 5. Cell charge current and cell charging power for different cell types.

Table 2. Comparison of LFP, LTO and NMC pouch-type battery cells. Sources: Datasheets from EIG, European Batteries, Altairnano, Kokam, Leclanche

		LFP	LTO	NMC
Cell voltage	V	≈3.2	≈2.3	≈3.6
Cell capacity	Ah	14...45	20...65	37...53
Energy density (gravimetric)	Wh/kg	115...146	76...77	165...175
Charge rate (C-rate), continuous		1 C	4 C...10 C	2 C...3 C
Cycle life (at 100% DoD)		3000	10,000...20,000	1000...5000

calculated values for charge current and charge power per cell type, using the mean values from Table 2.

To compare these cell types for e-bus applications, we will assume a 12 m bus designed for a maximum standee density of $4/m^2$ (see Figure 3) which leaves about 3400 kg excess payload for the battery system. Furthermore, we assume the battery system, including electronics and cooling equipment, to have an energy density 0.6 times the energy density at cell level (calculated from catalogue data). Using the mean values from Table 2, the vehicle's battery capacity and maximum continuous charging power[4] can be determined, shown in Figure 6.

Figures 5 and 6 give an indication as to the potential use cases for each cell type. LTO permits the highest charging power of all technologies, however, owing to its comparatively low energy density, it has the lowest capacity. LTO is only applicable in opportunity-charging systems. NMC enables the largest capacity as well as high charging power and therefore lends itself both to OC and DC. LFP is only feasible in slow-charging situations like DC.

In actual system design, battery cost and cycle life have to be considered also. Cycle life is a function of the depth of discharge (DoD) per cycle: Deep cycles cause more battery wear than shallow cycles (Korthauer 2013). This is why,

---

[4] The calculation of maximum charging power assumes equal voltage in all systems considered.
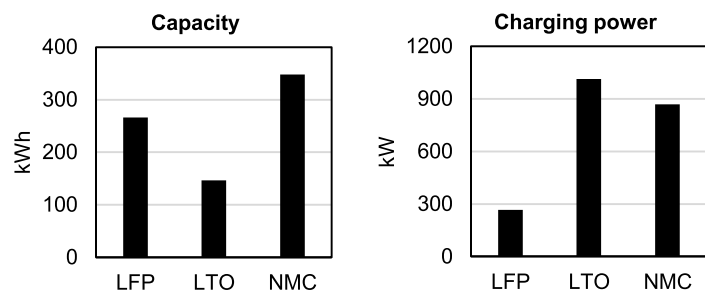
Figure 6. Battery capacity and maximum continuous charging power for a 3400 kg battery system with different cell types.

Table 3. Overview of vehicle charging interfaces

Type	Power [kW]		Contact time	Sources
	Continuous	Peak		
Schunk vehicle-side pantograph	375	750	<1 s	Schunk GmbH (2015, 2017)
ABB/Siemens wayside pantograph	n/a	600	≈5 s	Volvo Buses (2014) and Heuke (2017)
Bombardier induction system	200	200	≈5 s	Bombardier Transportation (2015)
CCS plug	∼100	n/a	n/a	Phoenix Contact GmbH (2013)

in opportunity-charging vehicles, a narrow DoD window is chosen (e.g., 40%), compared to 85%–90% for depot-charging vehicles.[5]

2.5. Charging systems

2.5.1. Charging interfaces

Various charging concepts are available for electric buses as described in the introduction. Depending on the charging concept, different interfaces are used for energy transfer, the most common of which are listed in Table 3.

In stationary *opportunity-charging* systems, there is currently a coexistence of several non-interoperable, automated charging interfaces. Conductive systems feature a pantograph that is either mounted on the roof of the vehicle or on a wayside pole (the latter also being referred to as an *inverted* pantograph). Inductive systems feature a coil beneath the road surface and a matching coil on the underside of the vehicle to enable wireless energy transfer; here, also, several incompatible solutions exist, e.g., systems with a fixed or shifting vehicle-side coil (Bombardier Transportation 2015; IPT Technology GmbH (IPT) 2016). To increase interoperability, the EU has instructed its standardisation agencies to develop a European standard for conductive charging interfaces by the end of 2019 and for inductive charging interfaces by the end of 2018 (European Commission 2015).

Depot-charging vehicles in Europe are usually equipped with an IEC 62196 based, manual plug interface (CCS, combined charging system). Opportunity-

---

[5] Values from own inspections and interviews with manufacturers.

charging buses generally also feature this interface not only to recharge the battery, but also to ensure thermal conditioning of the battery while parked in the depot.

2.5.2. Grid connection

Connection of charging infrastructure to the electricity grid is highly dependent on local circumstances. For example, depending on charging power and local grid capacity, individual opportunity-charging stations may be connected directly to the low-voltage grid (400 V), or they may have a dedicated transformer substation connected to the medium-voltage grid (10–20 kV). An energy storage unit (batteries or capacitors) can be implemented within the charging station to reduce peak load (Prenaj 2014). If charging stations are placed in proximity of existing tram infrastructure, it is possible to tap the tram's DC network without the need for additional transformer stations (Overkamp 2015). Electric bus depots usually require a dedicated substation connected to the medium-voltage grid; large depots (>200 vehicles) may even need a high-voltage grid connection (60–132 kV) with a distribution station (Crastan 2012; Lang 2017).

2.6. Auxiliaries

The auxiliary power demand is governed by the heating, ventilation and air-conditioning (HVAC) system and other auxiliaries.

2.6.1. HVAC system

The HVAC system is the most energy-consuming auxiliary in an electric vehicle (Braess & Seiffert 2013) and therefore must be given special attention in electric bus system design. Air conditioning of city buses is regarded by operators as an essential means to improve the service experience for customers (Verband Deutscher Verkehrsunternehmen (VDV) 2015). Current bus fleets in Europe are, indeed, mostly fully air-conditioned.[6]

A typical (diesel) city bus HVAC system includes a rooftop air-conditioning unit and floor-level convectors for heat distribution (Figure 7). The rooftop unit comprises a compression refrigeration machine and several heat exchangers for air cooling and heating. Water pipes link the rooftop unit and the floor-level convectors to the IC engine's cooling water circuit which is used as a primary heat source. An auxiliary diesel fuel heater mounted in the rear of the vehicle, not depicted in Figure 7, can supply additional heat to the water circuit.

HVAC systems currently implemented in electric buses mostly derive from this design and employ either the same diesel fuel heaters found in conventional buses (therefore not qualifying as fully zero-emission vehicles) or compatible electric resistance heaters. Cooling is also typically delivered by rooftop units.

Energy demand for resistance heating can, at worst, nearly triple the vehicle energy consumption, as a simple calculation shows. From our measurements on a 12 m electric bus, we estimate the average electric power necessary to keep the cabin at $17\,°C$ on a cold winter day with $-10\,°C$ ambient temperature (as illustrated in Figure 10) to be around 24 kW. Assuming a specific energy demand for traction and non-HVAC auxiliaries of 1.2 kWh/km – a plausible value

---

[6] Examples for the share of air-conditioned buses in urban bus fleets: Berlin 100% (Berliner Verkehrsbetriebe AöR 2013); Münster: 90% (Stadtwerke Münster GmbH 2015); Düsseldorf: >50% (Rheinbahn 2016); Milan.
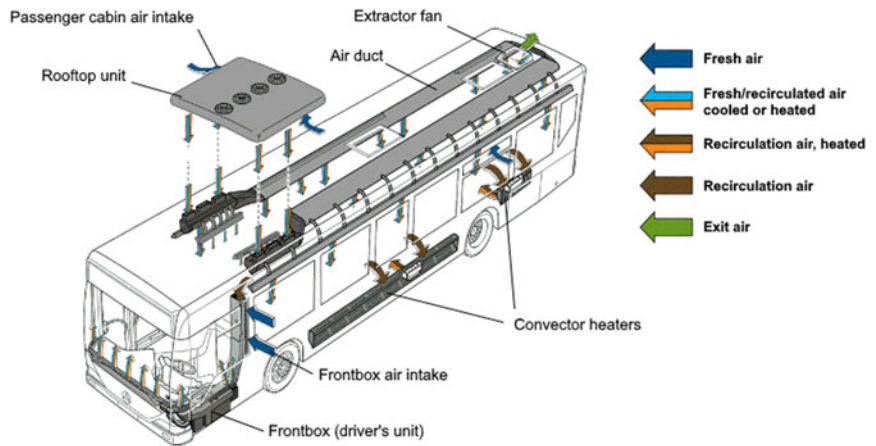
Figure 7. Typical city bus HVAC system. Reproduced and modified with kind permission from Evobus GmbH.

according to our measurements – a constant 24 kW load for heating will increase vehicle consumption by 1.3 kWh/km for an average velocity of 18 km/h (SORT 2) and 2 kWh/km for an average velocity of 12 km/h (SORT 1).[7] In comparison, cooling the vehicle in summer at an outdoor temperature of 35 °C with a typical 24 kW$_{th}$ chiller (Konvekta 2016) running at full load with a COP of 1.9 (calculated from catalogue data) will cause a compressor power demand of around 12.5 kW, leading to an increase in specific consumption of 0, 7 kWh/km for 18 km/h and 1, 0 kWh/km for 12 km/h. The critical design case in Central European climates is, therefore, the heating case.

Alternative HVAC designs primarily focus on reducing the heating energy demand. Electric heat pump (HP) systems comprise a reversible compression refrigeration circuit that enables both heating and cooling through the same device, while providing a more efficient heat supply than resistance heating (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2000). Some models allow for heat recovery from the traction battery, further increasing system efficiency (see, e.g., Ingersoll-Rand Company 2016). However, the capacity of a heat pump drops with ambient temperature, mandating the need for an electric or fuel-fired backup heater at low ambient temperatures (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2000). Based on catalogue data (Ingersoll-Rand Company 2016) and the above figures, the heating capacity deficit at −10 °C is estimated to be least 12 kW for a 12 m bus. Due to a lack of experimental data, we cannot validate this value at present.

Aside from efficient HVAC systems, electric buses offer potential for demand-side optimisation. Possible measures include improved thermal insulation, double-glazed windows (as known from long-distance coaches), door air curtains and improved control systems (Jefferies *et al.* 2015). However, experimental data assessing the effectiveness of these measures is, thus far, unavailable to the research community.

[7] For an explanation of SORT driving cycles, see Section 3.1.
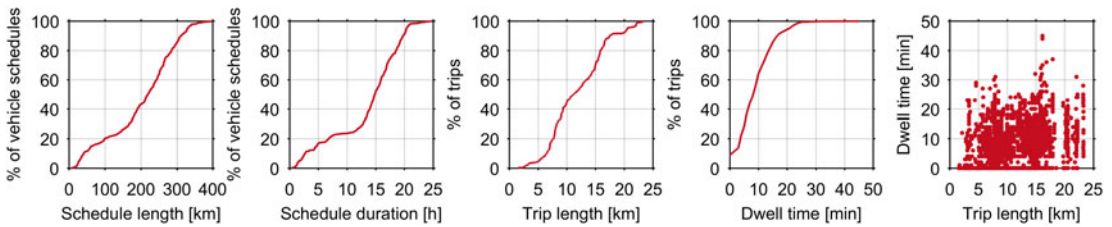
Figure 8. Cumulative distributions showing the length and duration of vehicle schedules, the length of passenger trips and the dwell time after passenger trips; correlation of dwell time and trip length. 39 routes of an urban bus network were analysed, covering 469 vehicle schedules and 8545 passenger trips. Empty trips were not considered.

2.6.2. Other auxiliaries

Besides the HVAC system, there are other auxiliaries like battery cooling, air compressor, steering pump and lights. According to our measurements on a 12 m electric bus, the power demand of the high-voltage auxiliaries is lower compared to the HVAC system: Air compressor max. 5 kW and steering pump max. 2.75 kW. Both systems are only infrequently in operation. The battery cooling unit (4 kW_{th}) was found to have a maximum electric power of 2.75 kW and to be in constant operation on hot summer days. Furthermore, a 500 W battery heater is operational on cold days.

3. General requirements

A holistic electric bus system design first needs to analyse the requirements of an urban bus system. This includes the daily operation range, distance of trips, driving pattern and idle time at end stops.

Depending on the charging technology used, deployment of electric buses may be limited by schedule length (i.e., the distance covered by a vehicle before it returns to the depot) or by a combination of individual trip length and subsequent dwell time. An investigation carried out for a sub-network of a public transit operator reveals the typical range and distribution of these parameters encountered in metropolitan areas (Figure 8). In particular,

- 95% of all vehicle schedules cover a distance shorter than or equal to 330 km, while the maximum distance observed was 407 km; also, 95% of vehicle schedules operate for 20.4 h or less, the maximum schedule duration observed being 24.7 h.

- 95% of all passenger trips are shorter than or equal to 20.6 km, the longest being 23.3 km.

- Dwell times – serving the purpose of driver recreation and compensating for service delays – vary considerably between zero and 45 min while not correlating with trip length; nearly 9% of all trips are followed by zero dwell time before commencing the next trip. This occurs especially at early morning or late night hours with low service delays, or if the next trip is a non-passenger trip (i.e., the vehicle is transferred to a depot or to another route).
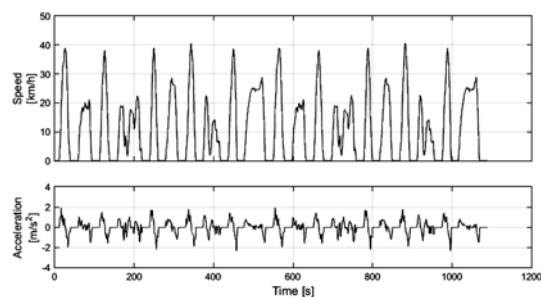
**Figure 9.** Speed and acceleration Manhattan bus cycle.

Table 4. Overview of chassis dynamometer driving cycles for buses with realistic urban drive patterns (Giakoumis 2017)

	NYBus	ADEME	MAN	BRA	OCC
Duration [s]	600	1898	1089	1740	1909
Distance [km]	0.98	5.68	3.32	10.87	10.5
Max speed [km/h]	49.57	47.9	40.72	58.2	65.39
Average vehicle speed [km/h]	5.94	10.77	10.99	22.5	19.85
Average driving speed [km/h]	17.12	15.5	16.71	29.48	24.7
Accelerations per km [1]	17^8	12.33	12.63	7.63	8.36
Idling time [%]	65	31	34	24	20
Stops per km [1]	12.13	7.04	6.32	2.76	3.04
Average stop duration [s]	32.67	14.48	17.76	13.73	11.72

3.1. Line characteristic

In addition, energy consumption per trip is a major design factor, influenced by the driving pattern, the topology, the climate conditions and the payload.

The UITP defines three synthetic driving patterns (standardised on-road test cycles – SORT) reflecting heavy urban (SORT 1, 12 km/h), easy urban (SORT 2, 18 km/h) and suburban (SORT 3, 25 km/h) conditions (Union Internationale des Transports Publics (UITP) 2009). The cycles are designed for on-road energy consumption measurement and are comparable to the new European drive cycle (NEDC) for passenger cars. Additionally, driving cycles have been compiled from measured velocity profiles for dynamometer testing. These real driving cycles can also be used to approximate the energy consumption on actual bus lines through simulation without the need for velocity profile measurements. However, a flat topology is assumed. Table 4 summarises the specifications of common chassis dynamometer driving cycles with realistic urban drive patterns for buses including their frequent stops. These cycles are the New York bus cycle (NYBus), the ADEME RATP cycle (ADEME), the Manhattan bus cycle (MAN), the Braunschweig cycle (BRA) and the Orange County Cycle (OCC). For the following study, the heavy urban Manhattan bus cycle, shown in Figure 9, has been selected.
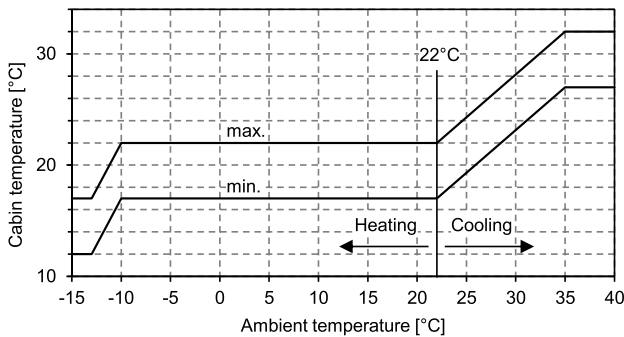
Figure 10. Required cabin temperature range as a function of ambient temperature according to Verband Deutscher Verkehrsunternehmen (VDV) 2015.
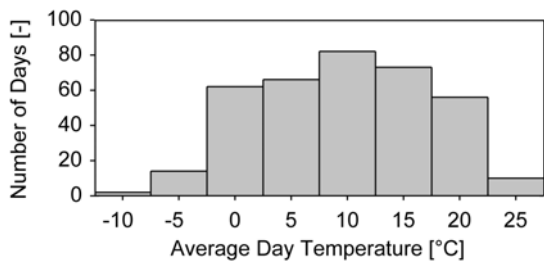
Figure 11. Long-term average yearly temperature distribution for Berlin, generated from Bundesinstitut für Bau-, Stadt- und Raumforschung (2013).

3.2. Climate data

The Association of German Transport Companies (VDV) has defined a standard for air-conditioned buses that requires the passenger cabin of a city bus to be kept within the temperature limits illustrated in Figure 10.

The HVAC system must operate under a wide range of outdoor temperatures, as Figure 11 shows for the example of Berlin.

4. Operational requirements and cost data

4.1. Operational assumptions

For a holistic electric bus system design we first need to define the operational conditions. In this study we assume a short bus line that is two times the Manhattan cycle with an overall length of 6.65 km and a dwell time of 10 min. Exemplarily, a 12 m single-deck bus is considered. The passenger occupancy is set to 20% (Verband Deutscher Verkehrsunternehmen (VDV) 2016). The power of auxiliaries in winter is set to maximum 24 kW, while the average auxiliary power is 8 kW (see Section 2.6.1). The battery capacity has to be chosen such that in winter conditions (scenario 1 in Table 5), the bus can be driven from terminus to terminus. Furthermore, we stipulate that in average conditions the unavailability of one charging station should not affect the normal operation service, hence the

---

[8] This value has been taken from the source (Barlow *et al.* 2009).

Parameters and input data

Operational Data
- Line characteristics
  - Velocity profile
    v = f(time)
  - Altitude
    h = f(route)
  - Including passenger occurance
    and time at stops
- Climate Data
  - Temperature
  - Solar radiation
- Operational Assumptions
  - Number of round trips
    until recharging
  - Max dwell time

Battery and Charge Sytem
- Battery cell properties
  - Battery type
  - Volume and weight
  - Discharge curve
  - Capacity
  - Wiring
  - SoC range [SoC$_{min}$, SoC$_{max}$]
- Charging system
  - Nominal charging power
  - Volume and weight
  - Delay time
  - Transmission efficiency

Vehicle Data
- Body type
  - Curb weight (without battery
    and charge system)
  - Max. additional weight through
    battery and charging system
  - Front area
  - Drag coefficient
- Drivetrain
  - Gear ration
  - Type of driving machine
  - Nominal power
  - Rolling resistance
  - Tyre diameter
- Auxiliaries
  - Aux. power, P = f(time, temp)

Simulation model

Results

Energy consumption	Required charging time	Additional weight	Charging efficiency

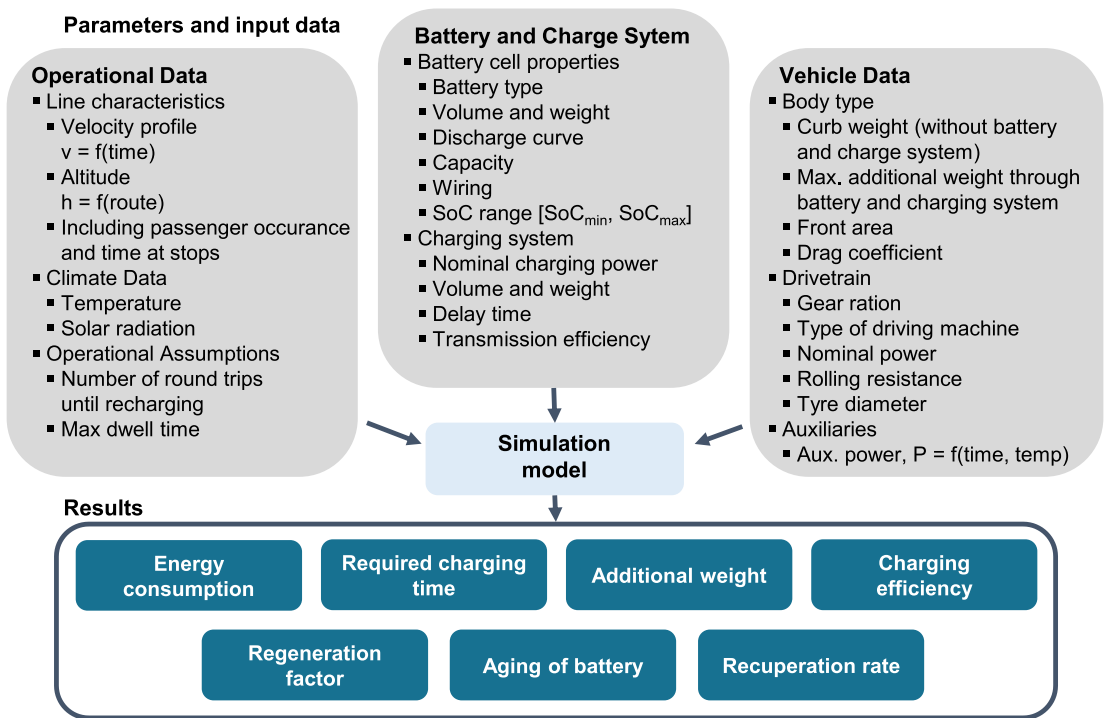| Regeneration factor	Aging of battery	Recuperation rate

Figure 12. Input and output data for bus system simulation.

vehicle range must be sufficient to cover two trips from terminus to terminus (i.e., one round trip, scenario 2 in Table 5).

4.2. Cost data

Cost data for the economical assessment, shown in Tables 6 and 7, has been derived from extensive literature review and interviews with experts from European manufacturers (Kunith 2017).

5. Electric bus system simulation model

After defining the requirements of urban buses and depicting the different characteristics of electric bus systems, the following section focuses on the technical assessment of urban bus systems based on a modular bus system simulation model. This model can be used to design a suitable battery system with a given SoC window, and an appropriate charging system for a certain bus line. Design parameters can be determined by taking into account bus schedules and weather conditions. In the following, the vehicle simulation model with its sub-models is presented. The exhaustive description of the sub-models and their respective application can be found in Göhlich, Kunith & Ly (2014), Jefferies *et al.* (2015) and Ly, Göhlich & Heide (2016). In Figure 12 the input and output data for the bus system simulation are shown.

5.1. Model description

In order to determine design parameters, an appropriate simulation model has been developed.

The parameters are examined for specific bus systems under specific operational conditions. Therefore, the input data covers operational data, as described in Section 4.1, vehicle data, battery cell properties and charging system data.

The traction energy consumption is dependent on the sum of resistance forces F_{res}, shown in Equation (1).

$$F_{res} = \lambda_m m \dot{v} + mg f_R \cos(\alpha) + \tfrac{1}{2} \rho_L c_W A v^2 + mg \sin(\alpha). \qquad (1)$$

In Equation (1), the mass m contains the bus kerb weight and the payload with the additional weight of charging system, battery system and passengers. λ_m is the mass factor and takes rotational masses into account. The vehicle speed v is given by the driving cycle, e.g., the Manhattan bus cycle in Figure 8. g is the gravity, f_R is the rolling resistance, α is the grade of the road, ρ_L is the air density, c_W is the drag coefficient and A is the front area of the bus.

With the resistance forces, the motor characteristic (η_{drive} determined from efficiency map in Section 2.3) and the auxiliary power demand P_{aux}, it is possible to determine the total required battery power P_{total}:

$$P_{total} = \frac{F_{res} v}{\eta_{drive}} + P_{aux}. \qquad (2)$$

Auxiliary power demand is chiefly dependent on the electric power of the HVAC system P_{HVAC}; contributions by other components (see Section 2.6.2) are summarised in P_{others}:

$$P_{aux} = P_{HVAC} + P_{others}. \qquad (3)$$

P_{HVAC} is determined by an HVAC system model coupled to a thermal model of the passenger cabin, as depicted in Figure 13. It results from the net total heating or cooling load and the efficiency of the HVAC system. Various HVAC systems are considered, including electric resistance heater, compression heat pump, diesel fuel heater and compression refrigeration unit. In the case of resistance and diesel heaters, constant efficiencies from manufacturer datasheets are assumed; for heat pumps and refrigeration units, a variable efficiency is calculated from a refrigerant circuit model parameterised using manufacturers' data. The passenger cabin model includes convective and radiation heat exchange with the environment, inner thermal loads and air exchange through open doors (Göhlich et al. 2015; Jefferies et al. 2015).

5.2. Model validation

The simulation results were validated by equipping two 12 m battery-electric buses with data gathering equipment and driving 19 round trips on a heavy urban cycle. The data gathering equipment recorded bus speed, auxiliary power, battery state of charge as well as various temperatures and control signals.

Figure 14 illustrates a measurement of a trip without HVAC usage and without passengers, used to validate the drivetrain and battery model. The recorded speed profile was used as an input for the simulation. The measured and simulated
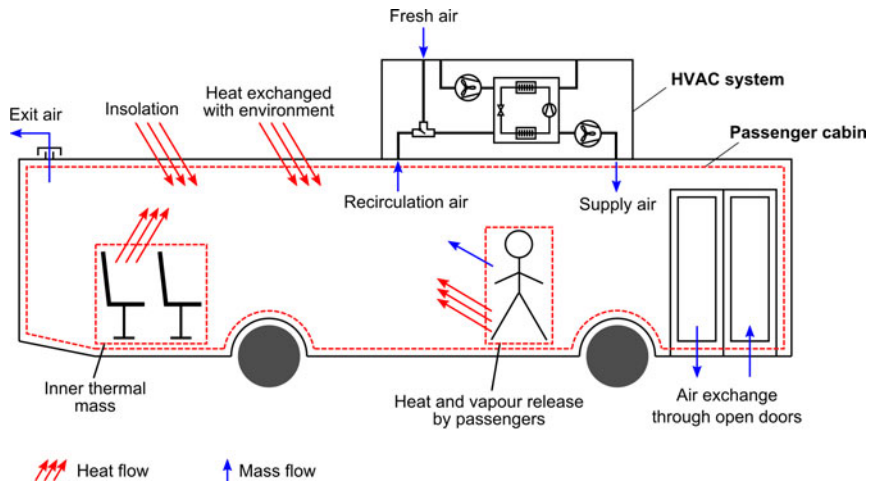
Figure 13. Passenger cabin and HVAC system model; image based on Jefferies *et al.* (2015).
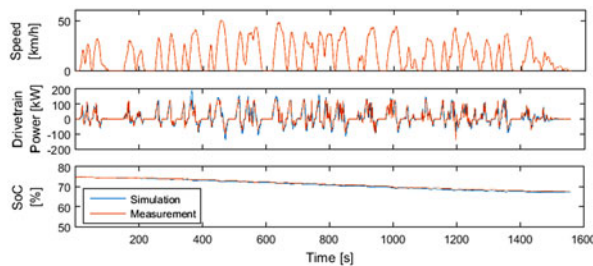
**Figure 14.** Comparison of the measured and simulated electric drivetrain power and SoC depletion based on a real measured driving cycle without HVAC system.

drivetrain power are in good agreement and the SoC can be predicted with an error margin of less than 1%.

To validate the passenger cabin sub-model, heating and cooling cases were considered. Prior to the measurement, the passenger cabin was heated up or cooled down using the on-board HVAC system until steady state was reached. The HVAC system was then turned off and several trips were carried out on a heavy urban bus cycle. The model was validated by using the recorded ambient temperature and vehicle speed as inputs and subsequently comparing the simulated cabin temperature with the measured cabin temperature, as Figure 15 illustrates for a sample test drive. Simulated and measured cabin temperature deviate by no more than 1.5 K. Further validation of the HVAC model is still in progress.

5.3. Model application and technology pre-selection

The application of the bus system simulation model is demonstrated for two charging strategies: depot charging (DC) and opportunity charging (OC).
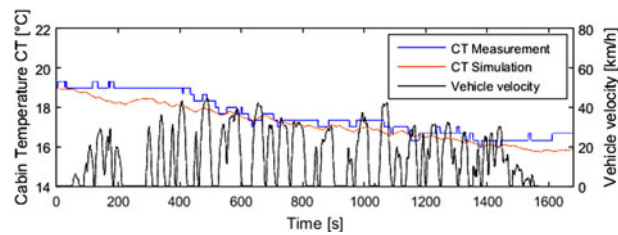
Figure 15. Electric bus drive cycle and cabin temperature (measurement and simulation, heating case).

Table 5. Operational assumptions

	Scenario 1	Scenario 2
Battery weight limitation	3400 kg	3400 kg
Dwell time at terminus	10 min	10 min
Passenger occupancy	65%	20%
Auxiliary power	24 kW	8 kW

For DC, we assume charging via a manual plug. For OC, we considered two different charging interfaces: pantograph and induction.

As shown in Section 2.4, LFP batteries are most suitable for slow charging in the depot, whereas LTO and NMC batteries permit high charging power and are therefore suitable for opportunity charging.

The NMC battery is suitable for both OC and DC. However, the specific cost of NMC batteries is nearly double that of LFP batteries (see Table 7), therefore, for DC only LFP is considered. The resulting five simulation cases are shown in Table 8. The maximum charging power provided by the wayside charging system is an upper limit, but the actual charging power is governed by the specific battery design and may be lower.

Further parameters for batteries and charging systems required for the simulation are summarised in Ly *et al.* (2016).

For the OC case, the required vehicle range is determined by the scenarios set out in Section 4.1 and the SoC window is set to 30%–70%. For this application, this is a plausible value according to our interviews with battery manufacturers, limiting high-cycle fatigue of the battery. For the DC case, the most critical parameter is the vehicle range, thus we will choose the maximum battery capacity bounded by the weight limitations (see Table 5). The SoC window for this case is set to 10%–95%.

With these parameters a vehicle simulation is performed for the scenarios described in Section 4.1. The scenario with the greater energy demand is chosen as the design case. The specific layout of the battery system (number of cells in series and in parallel) is determined from total energy consumption and maximum vehicle power demand as shown in Ly *et al.* (2016). This may result

[9] Currently, inductive charging stations of 300 kW and 450 kW are not available.

Table 6. Cost data for bus and infrastructure procurement in 2017 based on Kunith (2017)

Cost data/bus technology	Diesel	Inductive OC	Conductive OC	Depot charging
Vehicle				
12 m single-deck bus w/o battery (€)	270,000	380,000	340,000	330,000
Infrastructure				
Depot plug-in charging point 75 kW (€)	—	35,000	35,000	35,000
Fast-charging station 200 kW (€)	—	240,000	200,000	—
Fast-charging station 300 kW (€)	—	—[9]	300,000	—
Fast-charging station 450 kW (€)	—	—	400,000	—
Power transformer fast charging (€)	—	50,000	50,000	—

Table 7. Cost data for battery procurement in 2017 based on Kunith (2017)

Cost data/battery technology	LTO	NMC	LFP
Battery storage system (€/kWh)	950	800	430

Table 8. Simulation cases

Case	Charging interface	Charging strategy	Maximum charging power	Battery type	Charging rate
Inductive OC – NMC	Induction	OC at terminus	200 kW	NMC	3C
Inductive OC – LTO	Induction	OC at terminus	200 kW	LTO	4C
Conductive OC – NMC	Pantograph	OC at terminus	375 kW	NMC	3C
Conductive OC – LTO	Pantograph	OC at terminus	375 kW	LTO	4C
DC – LFP	Plug	DC	75 kW	LFP	1C

in slightly different battery capacities for each case despite identical operational requirements.

Figure 16 shows the resulting battery capacity and additional weight for the five cases listed in Table 8. Figure 17 illustrates the charging time and the actual charging power including the transmission efficiency of the charging interface and the C-rate of the battery technology. In the case of conductive OC, the maximum wayside charging power of 375 kW cannot be used by the NMC battery system.

The simulation results in Table 9 reveal that all selected bus concepts are feasible and the charging power of 200 kW is sufficient for the battery to be recharged within the dwell time. Since the installed charging power highly influences the total cost, OC systems are restricted to 200 kW in the subsequent economic analysis. With the specific parameters used for this study, the performance of NMC based systems is superior compared to LTO based systems in terms of cost and weight. Therefore, the subsequent economic analysis
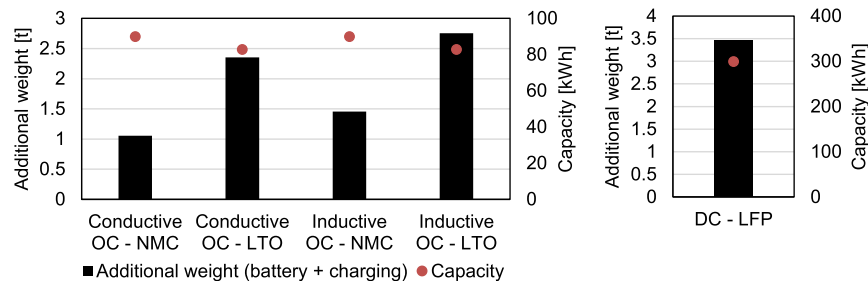
Figure 16. Additional weight and battery capacity of the different bus system designs for OC.
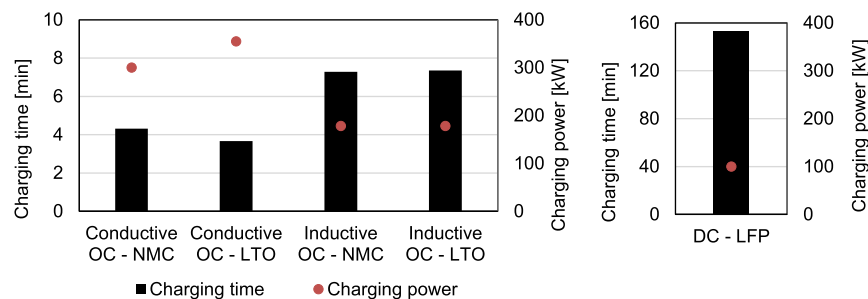

Figure 17. Charging time and actual charging power of the different bus system designs under winter conditions.

Table 9. Performance characteristic of selected bus concepts under average condition

Name	Battery capacity kWh	Battery cost k€	Charging time per trip min		Energy consumption kWh/km	
			Scenario 1	Scenario 2	Scenario 1	Scenario 2
Inductive OC – NMC	90	72	7.3	3.9	3.25	1.72
Inductive OC – LTO	83	79	7.4	3.9	3.28	1.75
Conductive OC – NMC	90	72	4.3	2.2	3.25	1.69
Conductive OC – LTO	83	79	3.7	1.9	3.26	1.73
DC – LFP	300	135	205 (per day, in depot)		3.33	1.83

will be limited to OC systems with NMC batteries and, as explained above, DC systems with LFP batteries.

6. Electric bus TCO model

The following section covers the economic assessment of bus line electrification. Here, we merge the operational and technological aspects of electric bus service with economic figures in order to determine the total cost of electrification. The presented approach is based on a TCO model including all costs occurring during

Parameters and input data
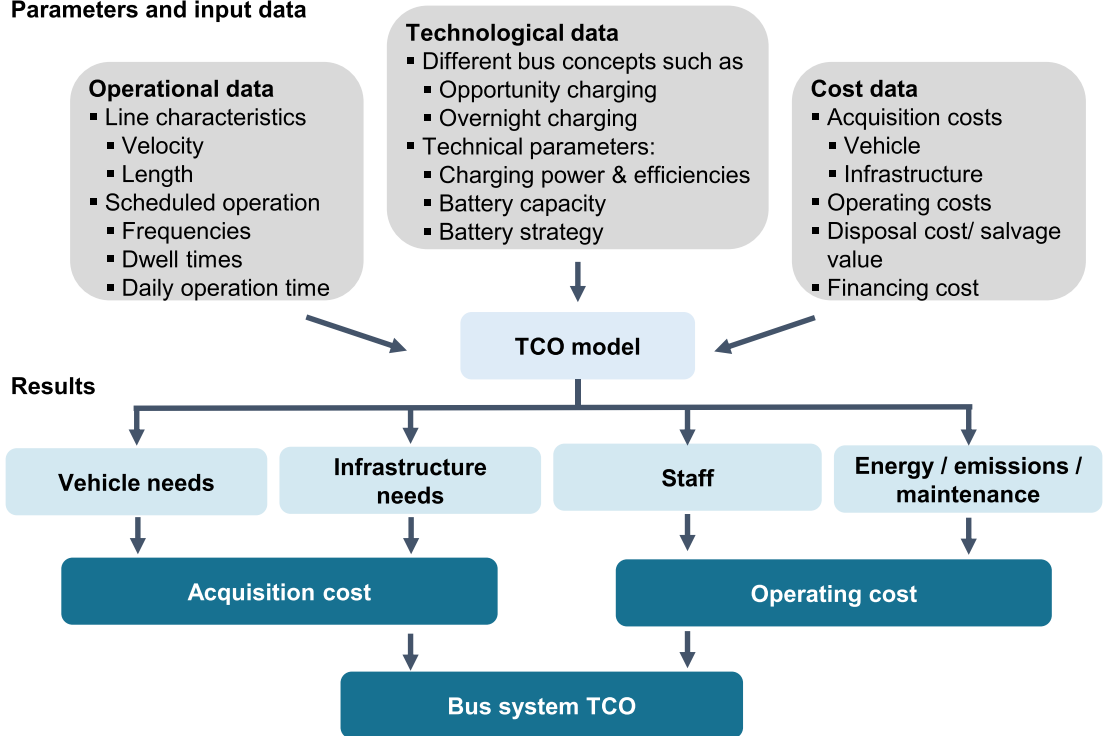
**Figure 18.** TCO model for the bus line electrification assessment.

the life cycle of a bus system, allowing for an objective technology selection. The model features and data requirements are described and the evaluation of a reference bus line is conducted.

6.1. Model description

The TCO model is composed of acquisition and operational cost for vehicles and infrastructure (en route and in the depot), capital financing cost, personnel cost and emission cost. It is based on the net present value method. As shown in Figure 18, the model input comprises operational, technical and cost data. The final TCO value is expressed in €/km based on the total mileage over the operational period.

Our TCO model (Göhlich *et al.* 2014; Kunith 2017) focuses on the evaluation of individual bus lines with a given schedule. For each technology, the required numbers of vehicles and charging stations have to be determined such that the bus schedule can be retained. The bus and infrastructure configuration as well as the technology-specific energy consumption have been determined in Sections 3–5. To obtain the operational cost, the calculation of annual energy demand, vehicle and infrastructure maintenance cost as well as technology-specific personnel cost are necessary.

Future developments of all cost elements are considered over the operational period. To forecast the cost of technical systems, a component-based experience curve approach is selected. A simplified cost structure of the bus systems is
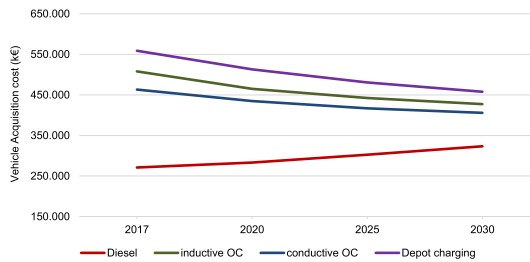
Figure 19. Forecasting vehicle acquisition cost for the trend scenario.

assumed where individual bus components are aggregated into component groups or vehicle sub-systems such as battery system or charging components. For the sub-systems, the cost reduction potentials are determining using learning rates based on market forecasts. In order to cope with uncertainties of future energy cost, a stochastic modelling of critical input parameters is performed. Finally, the *project-evaluated-and-review-technique* (PERT) method, which depicts cost trends via the beta distribution, is used to derive a distribution function from discrete prognosis values (Göhlich *et al.* 2013).

6.2. Model application and results

Based on the pre-selection shown in Section 5, the TCO assessment is conducted for two OC cases, one DC case and standard diesel buses as a reference case.

The input data for the TCO model is obtained from a series of demonstration studies on electric buses and interviews with transport authorities and manufacturers. Operating lifetime of vehicles is assumed to be 12 years, battery 6 years and infrastructure 20 years. After this period, the salvage value is set to zero.

For each case, three cost scenarios were evaluated: a probable cost development (trend scenario), an optimistic and a pessimistic cost degression for electric bus systems. The vehicle acquisition cost projections for the trend scenario are shown in Figure 19. Increasing production volume and technology advancements of electric buses will lead to significant cost reduction. Especially the increasing production volume of vehicle batteries (not only for buses but also for passenger cars) will lead to significant cost reduction (Thielmann, Sauer & Wietschel 2015). However, within the time span considered, vehicle acquisition cost for electric bus systems remains higher than for diesel buses.

Figure 20 shows the TCO values for electric 12 m buses compared to conventional buses under operational and technical parameters obtained in Sections 4 and 5.

The assessment is conducted for a procurement in the year 2017 and in 2025, respectively. The assumed cost input data corresponds to the aforementioned trend scenario with moderate cost developments. Under the conditions examined, the current deployment of electric bus systems leads to higher total cost in 2017, but for 2025, both conductive and inductive OC concepts become the most cost-effective solutions. The OC concept benefits from lower battery cost and an unchanged fleet size compared to the reference diesel fleet. By contrast, DC requires additional vehicles due to range limitations and hence causes higher
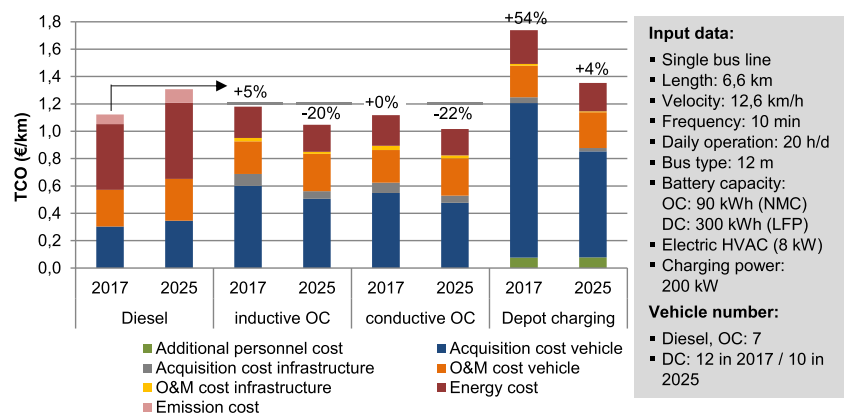
Figure 20. TCO assessment of different technologies for 2017 and 2025 (forecast trend scenario).
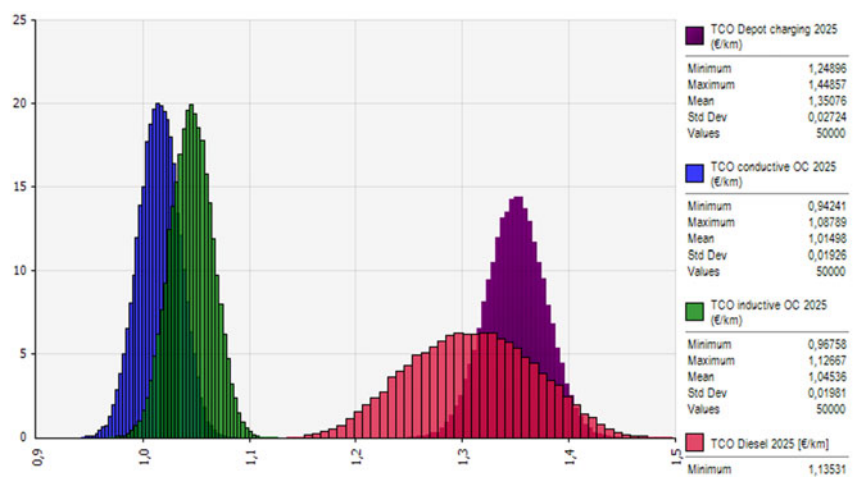

Figure 21. Stochastic TCO simulation for a bus procurement in 2025 based on selected route.

acquisition and staff cost. The number of required additional buses for DC is determined based on operational scenario 1 (see Section 4).

The integrated PERT method combined with a stochastic simulation allows the evaluation of the cost variation impacts. Figure 21 shows possible probability distribution of future TCO outcomes for different technologies in the year 2025, allowing a risk assessment for technology decisions. The spread of each histogram indicates the degree of cost uncertainty. For instance, the conventional diesel bus features the highest uncertainty due to the dependency on fossil fuel.

7. Conclusion and future work

The transformation process from diesel to electric bus systems opens up a very large design space. In this paper, all relevant vehicle technologies and charging systems are analysed and structured using a morphological matrix. Energy

consumption is analysed considering the characteristics of different electric powertrains and batteries. As heating and air conditioning are typically the most energy-consuming auxiliaries in electric buses, special attention was given to the HVAC system.

With the help of a verified modular simulation model, the vast variety of theoretical system solutions can be reduced to a subset of technically feasible variants. The final technology selection is based on a detailed economic analysis which is conducted by means of a TCO model.

We have applied the methodology to an exemplary bus line considering realistic operational aspects and viable cost input data. Uncertainties in future cost predictions have been considered using a stochastic modelling of critical input parameters.

The proposed methodology is suitable to support metropolitan bus operators in making a systematic procurement decision. Also, it can aid original equipment manufacturers (OEM) of electric buses and related infrastructure in making systematic design decisions.

Our results indicate that electric bus systems are technically feasible and can become economically competitive from the year 2025 and we have identified OC as the 'most suitable system solution' considering available technologies and operational requirements.

Recent transformation initiatives in Norway and the Netherlands support our findings (VDL Bus & Coach bv 2017; Waschbusch 2017). However, other bus operators are favouring DC. Especially the most extensive bus electrification project to date, the introduction of 16,000 electric buses in Shenzen, exclusively favours DC (Coren 2018). Here, LFP batteries are employed, as proposed in this paper for depot-charging systems.

It should be noted that our presented TCO model is based on fixed vehicle schedules and does not consider service delays which may result in higher energy consumption and lower available charging time. Also, the necessary transformation of bus depot processes is not yet incorporated in our model. A new depot simulation model is currently being developed to determine the effects of different operating processes on the charging behaviour. Also, an intelligent charging management for an electric bus fleet is considered and presented in Raab *et al.* (2017).

When planning the transformation of a complete bus network rather than a single line, cost efficient placement of charging infrastructure has to be considered. An approach to optimise the location of charging infrastructure based on a mixed-integer linear optimisation model has been presented in Kunith, Mendelevitch & Goehlich (2017). Furthermore, it can become necessary to adapt vehicle schedules to technological or operational constraints: In opportunity-charging systems, for example, it is possible that turnaround time at terminal stops has to be increased to allow sufficient charging time; with DC, on the other hand, existing vehicle schedules may have to be split to account for the limited vehicle range. A new algorithm to re-schedule vehicles to satisfy timetables and charging demand is currently under development by the Electric Transport Solutions research team at TU Berlin.

Acknowledgments

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Ed.) 2000 *ASHRAE Handbook. HVAC Systems and Equipment.*

Barlow, T. J., **Latham, S.**, **McCrae, I. S.** & **Boulter, P. G.** 2009 *A Reference Book of Driving Cycles for Use in the Measurment of Road Vehicle Emissions*, 3rd ed. Berkshire; checked on 9/22/2016.

Berliner Verkehrsbetriebe AöR (Ed.) 2013 *Bustypen der BVG.* Archived online document.

Berliner Verkehrsbetriebe AöR (Ed.) 2016 *Die Omnibusflotte der BVG.* Available online at http://unternehmen.bvg.de/de/?section=downloads&download=579, checked on 4/22/2017.

Bombardier Transportation (Ed.) 2015 *Primove Charging 200. Datenblatt.* Available online at http://primove.bombardier.com/fileadmin/primove/content/MEDIA/Publications/BT_PRIMOVE_charging_Fact_Sheet_2015_110dpi.pdf.

Braess, H.-H. & **Seiffert, U.** (Eds) 2013 *Vieweg Handbuch Kraftfahrzeugtechnik. 7*, Springer Vieweg, aktualisierte Auflage.

Bundesinstitut für Bau-, Stadt- und Raumforschung (Ed.) 2013 *Aktualisierte und erweitere Testreferenzjahre (TRY) von Deutschland für mittlere und extreme Witterungsverhältnisse.* Available online at http://www.bbsr-energieeinsparung.de/EnEVPortal/DE/Regelungen/Testreferenzjahre/Testreferenzjahre/01_start.html?nn=739044&notFirst=true&docId=743442, updated on 2013, checked on 4/28/2017.

Coren, M. J. 2018 *One city in China has More Electric Buses than all of America's Biggest Cities have Buses.* Edited by Quartz. Available online at https://qz.com/1169690, checked on 2/2/2018.

Crastan, V. 2012 *Elektrische Energieversorgung 1. Netzelemente, Modellierung, stationäres Verhalten, Bemessung, Schalt- und Schutztechnik. 3.* Springer, Aufl., Available online at doi:10.1007/978-3-642-22346-4.

European Commission (Ed.) 2011 *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Roadmap for Moving to a Competitive Low Carbon Economy in 2050.* Available online at http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0112&from=EN, checked on 5/15/2017.

European Commission 2015 Commission Implementing Decision of 12.3.2015 on a Standardisation Request to Draft European Standards for Alternative Fuels Infrastructure (M/533). Available online at ftp://ftp.cencenelec.eu/CENELEC/EuropeanMandates/M533_EN.pdf.

European Union 2015 Directive 2015/719 of the European Parliament and of the Council. In *Official Journal of the European Union - Legislation* (L 115). Available online at http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015L0719&from=EN.

European Union 2017 *Statistical Pocketbook. EU Transport in Figures*. Bietlot, Belgien; checked on 1/12/2018.

Faltenbacher, M., **Vetter, O.**, **Rock, A.** & **Grafetstätter, J.** 2016 *Statusbericht 2015/16 Hybrid- und Elektrobus-Projekte in Deutschland*. Edited by Bundesministerium für Verkehr und digitale Infrastruktur – BMVI. Berlin.

FCH JU (Ed.) 2012 *Urban Buses: Alternative Powertrains for Europe. A Fact-Based Analysis of the Role of Diesel Hybrid, Hydrogen Fuel Cell, Trolley and Battery Electric Powertrains. With assistance of McKinsey & Company*. Edited by FCH JU – The Fuel Cells and Hydrogen Joint Undertaking.

Gao, Z., **Lin, Z.**, **LaClair, T. J.**, **Liu, C.**, **Li, J.-M.**, **Birky, A. K.** & **Ward, J.** 2017 Battery capacity and recharging needs for electric buses in city transit service. *Energy* **122**, 588–600.

Giakoumis, E. G. 2017 *Driving and Engine Cycles*. Springer International Publishing, Cham; checked on 4/5/2017.

Göhlich, D., **Kunith, A.** & **Ly, T.** 2014 Technology assessment of an electric urban bus system for Berlin. In *URBAN TRANSPORT 2014. The Algarve, Portugal, 28.05.2014–30.05.2014* **(ed. C. A. Brebbia & J. W. S. Longhurst)**, pp. 137–149. WIT Press, Southampton, UK (WIT Transactions on The Built Environment).

Göhlich, D., **Spangenberg, F.** & **Kunith, A.** 2013 Stochastic total cost of ownership forecasting for innovative urban transport systems. In *IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2013, Bangkok, Thailand*, pp. 838–842. doi:10.1109/IEEM.2013.6962529.

Göhlich, D., **Ly, T.-A.**, **Kunith, A.** & **Jefferies, D.** 2015 Economic assessment of different air-conditioning and heating systems for electric city buses based on comprehensive energetic simulations. In *EVS28 International Electric Vehicle Symposium and Exhibition, Kintex, Korea, May 3–6* **(ed. Electric Vehicle Symposium (EVS))**. checked on 5/3/2017.

Heuke, A. 2017 OPPCHARGE: Eine Unterstützungsinitiative zur Standardisierung der Ladung von Elektrobussen. In *VDV-Akademie-Konferenz Elektrobusse - Markt der Zukunft* **(ed. Verband Deutscher Verkehrsunternehmen (VDV))**, vol. 8. Berlin.

Ingersoll-Rand Company (Ed.) 2016 *Thermo King Athenia MkII Electric Series. Datasheet*. Available online at http://europe.thermoking.com/bus/de/athe-mkii-elec.php, checked on 3/28/2017.

IPT Technology GmbH (IPT) (Ed.) 2016 *Competitive, Clean and Efficient Public Transport with IPT Charge Bus*. Available online at http://www.ipt-technology.com/images/files/CAT9200-0003b-EN_IPT_Charge_Bus.pdf, checked on 5/5/2017.

Jefferies, D., **Ly, T.**, **Kunith, A.** & **Göhlich, D.** 2015 Energiebedarf verschiedener Klimatisierungssysteme für Elektro-Linienbusse **(ed. Deutscher Kälte- und Klimatechnischer Verein (DKV))**. Deutsche Kälte- und Klimatagung, Dresden.

Konvekta, A. G. (Ed.) 2016 *Klimaanlagen UL 500 EM / 600 EM / 700 EM. Datenblatt*. Available online at http://www.konvekta.de/uploads/pics/UltraLight_500-700_EM_2.Gen_dt_engl_0916.pdf, checked on 4/24/2017.

Korthauer, R. 2013 Handbuch Lithium-Ionen-Batterien.

Kunith, A., **Mendelevitch, R.** & **Goehlich, D.** 2017 Electrification of a city bus network – an optimization model for cost-effective placing of charging infrastructure and battery sizing of fast charging electric bus systems. In *International Journal of Sustainable Transportation*, vol. 7, p. 0; doi:10.1080/15568318.2017.1310962.

Kunith, A. W. 2017 Elektrifizierung des urbanen öffentlichen Busverkehrs. Dissertation. Technische Universität Berlin, Berlin. Methoden der Produktentwiclung und Mechatronik, checked on 1/4/2018.

Lajunen, A. 2014 Improving the energy efficiency and operating performance of heavy vehicles by powertrain electrification. Dissertation. Aalto University, Espoo, Finnland. School of Engineering, checked on 11/28/2016.

Lajunen, A. & **Lipman, T.** 2016 Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy* **106**, 329–342.

Lang, J.-G. 2017 Vom Testfeld zum Masterplan. Die Lernkurve der HOCHBAHN aus 15 Jahren Elektromobilität **(ed. Verband Deutscher Verkehrsunternehmen (VDV))**, vol. 8. VDV-Akademie-Konferenz Elektrobusse - Markt der Zukunft, Berlin.

Li, Z. & **Hensher, D. A.** 2013 Crowding in public transport: a review of objective and subjective measures. *Journal of Public Transportation* **16** (2), 107–134.

Ly, T.-A., **Göhlich, D.** & **Heide, L.** 2016 Assessment of the interaction of charging system and battery technology for the use in urban battery electric bus systems. In *Vehicle Power and Propulsion Conference. The 13th IEEE Vehicle and Propulsion Conference. Hangzhou, China, 17–20.10.2016* **(ed. IEEE)**. IEEE; checked on 5/3/2017.

Mahmoud, M., **Garnett, R.**, **Ferguson, M.** & **Kanaroglou, P.** 2016 Electric buses. A review of alternative powertrains. *Renewable and Sustainable Energy Reviews* **62**, 673–684.

MAN Nutzfahrzeuge Gruppe 2008 *Grundlagen der Nuzfahrzeugtechnik. Basiswissen Lkw und Bus*. Kirschbaum Verlag, Bonn.

Neudorfer, H. 2016 Vergleich unterschiedlicher Antriebstechnologien für elektrische Busantriebe. *Trolleymotion Ebus Berlin*. Trolleymotion Ebus. Berlin, 31.05.2016.

Nurhadi, L., **Borén, S.** & **Ny, H.** 2014 A sensitivity analysis of total cost of ownership for electric public bus transport systems in Swedish medium sized cities. *Transportation Research Procedia* **3**, 818–827.

Omnibus Revue (Ed.) 2017 *Datenblatt Van Hool AGG300*. Available online at http://www.omnibusrevue.de/agg300-971419.html, checked on 4/22/2017.

Overkamp, W. 2015 *Nutzung von Straßenbahn-Infrastrukturen zur Ladung von Batteriebussen. Demonstrationsprojekt Oberhausen* **(ed. Verband Deutscher Verkehrsunternehmen (VDV))**, vol. 6. VDV-Akademie-Konferenz Elektrobusse, Berlin.

Phoenix Contact GmbH (Ed.) 2013 *Solutions for E-Mobility*. Available online at https://www.phoenixcontact.com/assets/downloads_ed/global/web_dwl_promotion/Bro_E-Mobility_Eng_low.pdf, checked on 5/3/2017.

Pihlatie, M., **Kukkonen, S.**, **Halmeaho, T.**, **Karvonen, V.** & **Nylund, N.-O.** 2014 Fully electric city buses – the viable option. In *International Electric Vehicle Conference 2014* **(ed. IEEE)**. checked on 11/4/2016.

Prenaj, B. 2014 TOSA flash elektrobus system: Erfahrungen und Perspektiven nach neun Monaten im öffentlichen Betrieb.**(ed. Verband Deutscher Verkehrsunternehmen (VDV))**, vol. 5. VDV-Akademie-Konferenz Elektrobusse, Berlin.

Raab, A. F., **Lauth, E.**, **Strunz, K.** & **Göhlich, D.** 2017 Implementation schemes for electrified bus fleets at intra-urban depots with optimized energy procurements in virtual power plant operations. In *The 30th International Electric Vehicle Symposium*.

Rheinbahn, A. G. (Ed.) 2016 *Gutes Klima in unseren Bahnen und Bussen*. Available online at https://blog.rheinbahn.de/2016/08/25/gutes-klima-in-unseren-bahnen-und-bussen/, checked on 4/26/2017.

Rogge, M., **Wollny, S.** & **Sauer, D.** 2015 Fast charging battery buses for the electrification of urban public transport—a feasibility study focusing on charging infrastructure and energy storage requirements. *Energies* **8** (5), 4587–4606.

Roland, B. 2015 *Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe*. Edited by FCH JU – The Fuel Cells and Hydrogen Joint Undertaking. Available online at http://www.fch.europa.eu/sites/default/files/150909_FINAL_Bus_Study_Report_OUT_0.PDF, checked on 6/6/2016.

Rothgang, S., **Rogge, M.**, **Becker, J.** & **Sauer, D.** 2015 Battery design for successful electrification in public transport. *Energies* **8** (7), 6715–6737.

Schunk GmbH (Ed.) 2015 *Schunk Smart Charging. Charging Systems for Battery-Powered Vehicles. Broschüre*. Available online at http://www.schunk-carbontechnology.com/uploads/tx_rmsschunktest/17-05e_SchunkSmartCharging_2015_02.pdf, checked on 5/3/2017.

Schunk GmbH (Ed.) 2017 *Schunk Smart Charging*. Available online at https://www.schunk-group.com/de/leistungsportfolio/schunk-carbon-technology/smart-charging/, checked on 5/3/2017.

Sinhuber, P., **Rohlfs, W.** & **Sauer, D. U.** 2012 Study on power and energy demand for sizing the energy storage systems for electrified local public transport buses. In *IEEE Vehicle Power and Propulsion Conference 2012. Seoul, Korea (South)* **(ed. IEEE)**. checked on 11/4/2016.

Stadtwerke Münster GmbH (Ed.) 2015 *Klimaanlagen: Damit es im Bus nicht zu heiß wird*. Available online at http://www.stadtwerke-muenster.de/blog/verkehr/damit-es-im-bus-nicht-zu-heiss-wird/, checked on 4/26/2017.

Thielmann, A., **Neef, C.**, **Hettesheimer, T.**, **Döscher, H.**, **Wietschel, M.** & **Tübke, J.** 2017 *Energiespeicher-Roadmap_Update 2017*. Edited by Fraunhofer-Institut für System- und Innovationsforschung ISI, checked on 1/12/2018.

Thielmann, A., **Sauer, A.** & **Wietschel, M.** 2015 Gesamt-Roadmap Energiespeicher für die Elektromobilität 2030. Available online at http://www.isi.fraunhofer.de/isi-wAssets/docs/t/de/publikationen/GRM-ESEM.pdf.

Union Internationale des Transports Publics (UITP) (Ed.) 2009 *UITP-Projekt 'SORT' Standardisierte Zyklen für Straßentests. Standardised On-Road Tests Cycles*, 2nd ed. Brüssel; checked on 8/7/2014.

VDL Bus & Coach bv 2017 10 VDL Citea Electrics in scheduled service in Groningen. Available online at http://www.vdlbuscoach.com/News/News-Library/2017/10-VDL-Citea%E2%80%99s-Electric-in-dienstregeling-Groninge.aspx, checked on 2/2/2018.

Verband Deutscher Verkehrsunternehmen (VDV) (Ed.) 2015 *VDV-Schrift 236: Klimatisierung von Linienbussen der Zulassungsklassen I und II, für konventionell angetriebene Diesel- und Gasbusse sowie für Hybrid-, Brennstoffzellen- und Elektrobusse*.

Verband Deutscher Verkehrsunternehmen (VDV) (Ed.) 2016 *2015. Statistik*. checked on 2/1/2018.

Volvo Buses 2014 *Premiere for Volvo's Electric Hybrid in Commercial Service*. Video. Available online at https://www.youtube.com/watch?v=FseBmNiqrd0, checked on 5/3/2017.

Waschbusch, L. M. 2017 *Tide Buss bestellt 25 vollelektrische Volvo-Busse*. Edited by Vogel Business Media GmbH & Co. KG. Available online at https://www.automobil-industrie.vogel.de/tide-buss-bestellt-25-vollelektrische-volvo-busse-a-650291/, checked on 2/2/2018.

ZeEUS Project (Ed.) 2016 *ZeEUS eBus Report. An Overview of Electric Buses in Europe*. Available online at http://zeeus.eu/uploads/publications/documents/zeeus-ebus-report-internet.pdf.

Zhang, X. & **Goehlich, D.** 2016 A novel driving and regenerative braking regulation design based on distributed drive electric vehicles. In *2016 IEEE Vehicle Power and Propulsion Conference (VPPC), Hangzhou, China, 17.10.2016–20.10.2016*, pp. 1–6. IEEE, checked on 4/20/2017.